

TeV scale model for neutrino masses, dark matter and leptogenesis

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Abstract. We present a TeV scale model for leptogenesis where the origin of neutrino masses are independent of the scale of leptogenesis. As a result, the model could be extended to explain *dark matter, neutrino masses and leptogenesis at the TeV scale*. The most attractive feature of this model is that it predicts a few hundred GeV triplet Higgs scalar that can be tested at LHC or ILC.

Keywords: Neutrino Masses, Leptogenesis, Dark Matter

In the type-I seesaw models [1] the physical neutrino masses are largely suppressed by the scale of lepton (L) number violation, which is also the scale of leptogenesis [2]. The observed baryon (B) asymmetry, defined by $(n_B/n_\gamma)_0 = (6.15 \pm 0.25) \times 10^{-10}$, and the low energy neutrino oscillation data combinely then give a lower bound on the scale of leptogenesis to be $\sim \mathcal{O}(10^9)$ GeV [3]. Alternately in the type-II seesaw models [4] it is equally difficult to generate L -asymmetry at the TeV scale because the interaction of $SU(2)_L$ triplets with the gauge bosons keep them in equilibrium up to a very high energy scale $\sim \mathcal{O}(10^{10})$ GeV [5]. Thus irrespective of the seesaw models, the scale of leptogenesis can not be less than $\sim \mathcal{O}(10^9)$ GeV [6]. This is because in these class of models the L -number violation required for neutrino masses and leptogenesis is same.

In a previous work [7] we proposed a new mechanism of leptogenesis at the TeV scale. We ensure that the lepton number violation required for the neutrino masses does not conflict with the lepton number violation required for leptogenesis. As a result the model could be extended to explain dark matter, neutrino masses and leptogenesis at the TeV scale. Moreover, the model predicts a few hundred GeV triplet Higgs scalar whose decay through the same sign dilepton signal could be tested at LHC or ILC.

The Model: We now describe the salient features of the model. In addition to the quarks, leptons and the usual Higgs doublet $\phi \equiv (1, 2, 1)$, we introduce two triplet Higgs scalars $\xi \equiv (1, 3, 2)$ and $\Delta \equiv (1, 3, 2)$, two singlet scalars $\eta^- \equiv (1, 1, -2)$ and $T^0 \equiv (1, 1, 0)$, and a doublet Higgs $\chi \equiv (1, 2, 1)$. The transformations of the fields are given under the standard model (SM) gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. There are also three heavy singlet fermions $S_a \equiv (1, 1, 0), a = 1, 2, 3$.

A global symmetry $U(1)_X$ allows us to distinguish between the L -number violation required for neutrino masses and the L -number violation required for leptogenesis. Under $U(1)_X$ the fields $\ell_{iL}^T \equiv (\nu, e)_{iL} \equiv (1, 2, -1)$, $e_{iR} \equiv (1, 1, -2)$, η^- and T^0 carry a quantum number 1, Δ , S_a , $a = 1, 2, 3$ and ϕ carry a quantum number zero, while ξ and χ carry quantum numbers -2 and 2 respectively. We assume that $M_\xi \ll M_\Delta$. However, as we shall see later, they contribute equally to the neutrino masses.

We now write down the Lagrangian symmetric under $U(1)_X$. The terms in the Lagrangian, relevant to the rest of our discussions, are given by

$$\begin{aligned} -\mathcal{L} \supseteq & f_{ij}\xi\ell_{iL}\ell_{jL} + \mu\Delta^\dagger\phi\phi + M_\xi^2\xi^\dagger\xi + M_\Delta^2\Delta^\dagger\Delta + h_{ia}\bar{e}_{iR}S_a\eta^- + M_{sab}S_aS_b + y_{ij}\phi\bar{\ell}_{iL}e_{jR} \\ & + M_T^2T^\dagger T + \lambda_T|T|^4 + \lambda_\phi|T|^2|\phi|^2 + \lambda_\chi|T|^2|\chi|^2 + f_T\xi\Delta^\dagger TT \\ & + \lambda_{\eta\phi}|\eta^-|^2|\phi|^2 + \lambda_{\eta\chi}|\eta^-|^2|\chi|^2 + V_{\phi\chi} + h.c., \end{aligned} \quad (1)$$

where $V_{\phi\chi}$ constitutes all possible quadratic and quartic terms symmetric under $U(1)_X$. We introduce the $U(1)_X$ symmetry breaking soft terms

$$-\mathcal{L}_{soft} = m_T^2 TT + m_\eta\eta^-\phi\chi + h.c.. \quad (2)$$

If T carries the L -number by one unit then the first term explicitly breaks L -number in the scalar sector. The second term on the other hand conserves L -number if η^- and χ possess equal and opposite L -number. This leads to the interactions of the fields $S_a, i = 1, 2, 3$ to be L -number conserving. As we shall discuss later, this can generate the L -asymmetry of the universe, while the neutrino masses come from the L -number conserving interaction term $\xi\Delta^\dagger TT$ after the field T acquires a vacuum expectation value (VEV).

At tree level the Higgs field Δ acquires a very small VEV

$$\langle\Delta\rangle = -\mu\frac{v^2}{M_\Delta^2}, \quad (3)$$

where $v = \langle\phi\rangle$, ϕ being the SM Higgs doublet. However, we note that the field ξ does not acquire a VEV at the tree level.

At a few TeV the scalar field T acquires a VEV. This gives rise to a mixing between Δ and ξ through the effective mass term

$$-\mathcal{L}_{\Delta\xi} = m_s^2\Delta^\dagger\xi, \quad (4)$$

where the mass parameter $m_s = \sqrt{f_T\langle T\rangle^2}$ is of the order of TeV, similar to the mass scale of T . The effective couplings of the different triplet Higgs scalars, which give the L -number violating interactions for neutrino masses, are then given by

$$-\mathcal{L}_{\nu-mass} = f_{ij}\xi\ell_{iL}\ell_{jL} + \mu\frac{m_s^2}{M_\Delta^2}\xi^\dagger\phi\phi + f_{ij}\frac{m_s^2}{M_\xi^2}\Delta\ell_{iL}\ell_{jL} + \mu\Delta^\dagger\phi\phi + h.c.. \quad (5)$$

The field ξ then acquires an induced VEV,

$$\langle \xi \rangle = -\mu \frac{v^2 m_s^2}{M_\xi^2 M_\Delta^2}. \quad (6)$$

The VEVs of both the fields ξ and Δ will contribute to neutrino masses by equal amount and thus the neutrino masses are given by

$$(m_\nu)_{ij} = -f_{ij} \mu \frac{v^2 m_s^2}{M_\xi^2 M_\Delta^2}. \quad (7)$$

Assuming that $M_\Delta \sim \mu \simeq \mathcal{O}(10^{15})$ GeV one can find M_ξ to be of the order of a few hundred GeV. This makes the model predictive since the decay of ξ through the same sign dilepton can be verified in the near future colliders (LHC/ILC).

Leptogenesis: Since the absorptive part of the off-diagonal one loop self energy terms in the decay of triplets Δ and ξ is zero, their decay can't produce any L -asymmetry even though their decay violate L -number. However, the possibility of erasing any pre-existing L -asymmetry through the $\Delta L = 2$ processes mediated by Δ and ξ should not be avoided. In particular, the important erasure processes are: $\ell\ell \leftrightarrow \xi \leftrightarrow \phi\phi$ and $\ell\ell \leftrightarrow \Delta \leftrightarrow \phi\phi$. If $m_s^2 \ll M_\Delta^2$ then the L -number violating processes mediated through Δ and ξ are suppressed by $(m_s^2/M_\xi^2 M_\Delta^2)$ and hence practically don't contribute to the above erasure processes. Thus a fresh L -asymmetry can be produced at the TeV scale.

Without loss of generality we shall work in a basis in which M_{sab} is diagonal and $M_3 > M_2 > M_1$, where $M_a = M_{saa}$. In this basis, the decay of the singlet fermions S_a , $a = 1, 2, 3$ generates an equal and opposite L - asymmetry between e_{iR}^- and η^+ fields through

$$\begin{aligned} S_a &\rightarrow e_{iR}^- + \eta^+ \\ &\rightarrow e_{iR}^+ + \eta^-, \end{aligned}$$

since e_{iR}^- and η^+ carry equal and opposite L - number. The one-loop self-energy and vertex-type diagrams that can interfere with the tree-level decays to generate a CP-asymmetry

$$\varepsilon = - \sum_i \left[\frac{\Gamma(S_1 \rightarrow e_{iR}^- \eta^+) - \Gamma(S_1 \rightarrow e_{iR}^+ \eta^-)}{\Gamma_{tot}(S_1)} \right] \simeq \frac{1}{8\pi} \frac{M_1}{M_2} \frac{\text{Im}[(hh^\dagger)_{i1}^2]}{\sum_a |h_{a1}|^2}. \quad (8)$$

If these two asymmetries cancel with each other then there should not be any left behind L -asymmetry. However, as we see from the Lagrangians (1) and (2) that none of the interactions that can transfer the L -asymmetry from η^- to the lepton doublets while e_R is transferring the L -asymmetry from the singlet sector to the usual lepton doublets through $\phi \bar{\ell}_L e_R$ coupling. Note that the coupling, through which the asymmetry between η^- and e_R^+ produced, is already gone out

of thermal equilibrium. So, it will no more allow the two asymmetries to cancel with each other. The asymmetry in the η fields is finally transferred to the χ fields through the trilinear soft term introduced in Eq. (2). The $B+L$ violating sphaleron processes then convert the L - asymmetry in the lepton doublets to a net B - asymmetry. Since the source of L -number violation for this asymmetry is different from the neutrino masses, there is no bound on the mass scale of S_1 from the low energy neutrino oscillation data. Therefore, the mass scale of S_1 can be as low as a few TeV.

Dark matter: As the universe expands the temperature of the thermal bath falls. As a result, below their mass scales, the heavy fields η^- and T^0 are annihilated to the lighter fields ϕ and χ . Notice that there is a surviving Z_2 symmetry of the Lagrangians (1) and (2) under which $S_a, a = 1, 2, 3$, η^- and χ are odd while all other fields are even. Since the neutral component of χ is the lightest one it can be stable because of Z_2 symmetry. Therefore, the neutral component of χ , having mass in a range 50 GeV - 100 GeV, behaves as a dark matter.

Collider Signature: The doubly charged component of the light triplet Higgs ξ can be observed through its decay into same sign dileptons [9]. Since $M_\Delta \gg M_\xi$, the production of Δ particles in comparison to ξ are highly suppressed. Hence it is worth looking for the signature of $\xi^{\pm\pm}$ either at LHC or ILC. Once it is produced, ξ mostly decay through the same sign dileptons: $\xi^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$. Note that the doubly charged particles can not couple to SM quarks and therefore the SM background of the process $\xi^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$ is quite clean and hence the detection will be unmistakable.

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